NASA

Ames Research Center

Progress in Unsteady Turbopump Flow Simulations

Cetin Kiris
William Chan
Dochan Kwak
NASA Ames Research Center

Robert Williams
NASA Marshall Space Flight Center

JANNAF 2002 Meeting, Destin, FL
April 8-12, 2002

1

NASA

Outline

Ames Research Center

- INTRODUCTION
  - Major Drivers of the Current Work
  - Objective
- SOLUTION METHODS
  - Summary of Solver Development
  - Formulation / Approach
  - Parallel Implementation
- UNSTEADY TURBOPUMP FLOW
  - Overset Grid System
  - Scripting Capability
  - Results
- SUMMARY

2

Major Drivers of Current Work

NASA

- To provide computational tools as an economical option for developing future space transportation systems (i.e. RLV subsystems development)

  Impact on component design   ⇒ Rapid turn-around of high-fidelity analysis
  Increase durability/safety   ⇒ Accurate quantification of flow
                                    (i.e. prediction of flow-induced vibration)

  Impact on system performance ⇒ More complete systems analysis
                                  using high-fidelity tools

- Target
  Turbo-pump component analysis ⇒ Entire sub-systems simulation

  Computing requirement is large.
  ⇒ The goal is to achieve 1000 times speed up over what was possible in 1992

  → done already
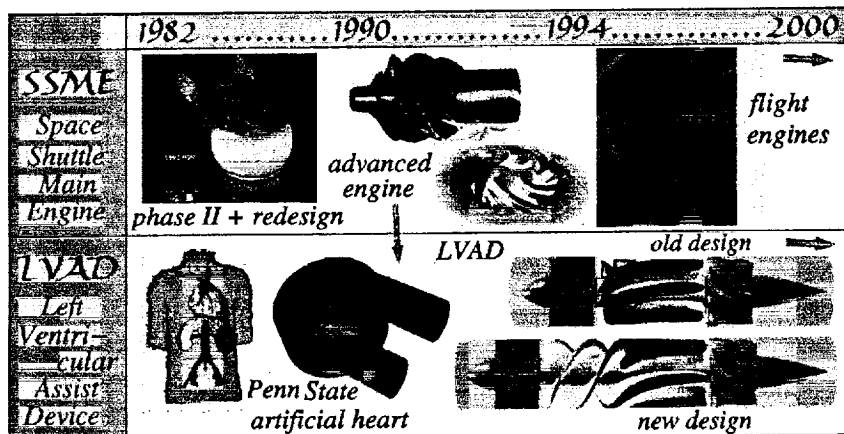
3

Current Challenges

NASA

- Challenges where improvements are needed
  - Time-integration scheme, convergence
  - Moving grid system, zonal connectivity
  - Parallel coding and scalability

- As the computing resources changed to parallel and distributed platforms, computer science aspects become important.
  - Scalability (algorithmic & implementation)
  - Portability, transparent coding, etc.

- Computing resources
  - "Grid" computing will provide new computing resources for problem solving environment
  - High-fidelity flow analysis is likely to be performed using "super node" which is largely based on parallel architecture

4

● To enhance incompressible flow simulation capability for developing aerospace vehicle components, especially, unsteady flow phenomena associated with high speed turbo pump.

	1982 ....1990 ....1994 2000
SSME Space Shuttle Main Engine	phase II + redesign advanced engine flight engines
LVAD Left Ventri- cular Assist Device	LVAD old design Penn State artificial heart new design

---

● Time-integration scheme

Artificial Compressibility Formulation

· Introduce a pseudo-time level and artificial compressibility
· Iterate the equations in pseudo-time for each time step until incompressibility condition is satisfied.

Pressure Projection Method

· Solve auxiliary velocity field first, then enforce incompressibility condition by solving a Poisson equation for pressure.

6

Time-Accurate Formulation

· Discretize the time term in momentum equations using second-order three-point backward-difference formula

$$\left(\frac{\partial U}{\partial \xi}+\frac{\partial V}{\partial \eta}+\frac{\partial W}{\partial \zeta}\right)^{n+1}=0 \; ; \; \frac{3q^{n+1}-4q^{n}+q^{n-1}}{2\Delta t}=-r^{n+1}$$

· Introduce a pseudo-time level and artificial compressibility,
· Iterate the equations in pseudo-time for each time step until incompressibility condition is satisfied.

$$\frac{1}{\Delta \tau}\left(p^{n+1,m+1}-p^{n+1,m}\right)=-\beta\nabla q^{n+1,m+1}$$

$$\frac{1.5}{\Delta t}\left(q^{n+1,m+1}-q^{n+1,m}\right)=-r^{n+1,m+1}-\frac{3q^{n+1,m}-4q^{n}+q^{n-1}}{2\Delta t}$$

7

● Time History of Stagnation Point

EXP (Taneda, 1971)
INS3D-UP
INS3D-FS
Finite Elem. Sol. (Yoshida, 1985)
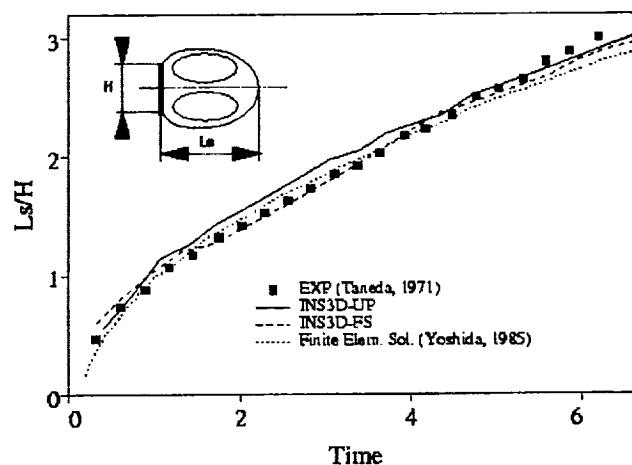
- Time History of Stagnation Point
  Artificial compressibility incorporated with Poisson solver

INS3D-UP / DT=0.0825
■ EXP. (Taneda, 1971)
—— LINE-RELAXATION, NSUB=10
- - - - GMRES-ILU(0), NSUB=10
— - — - L-REL.,POISSON SOL, NSUB=2

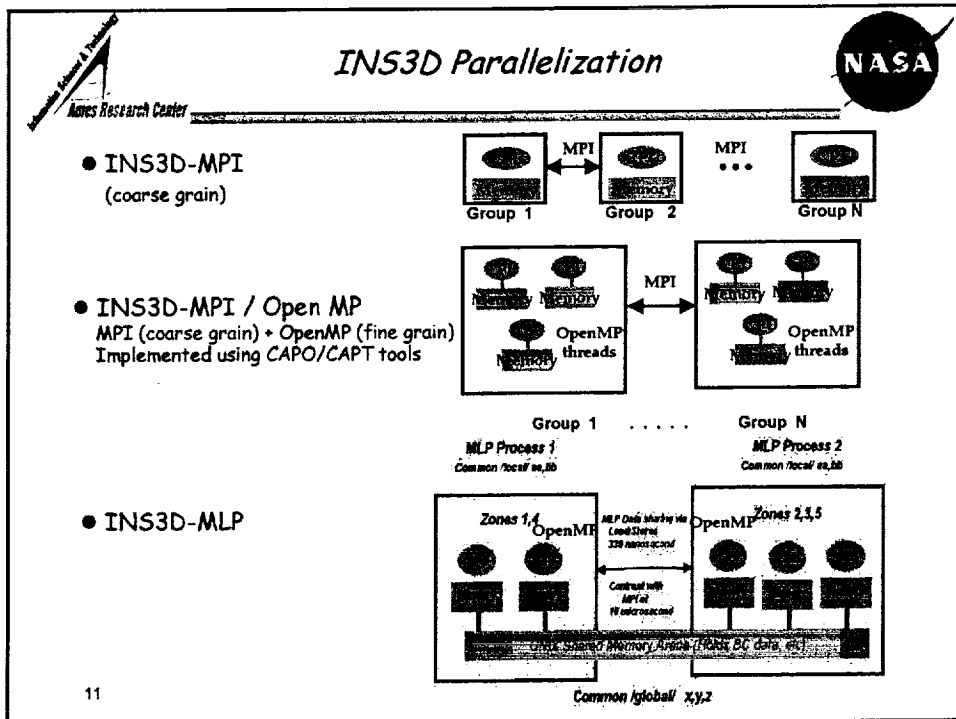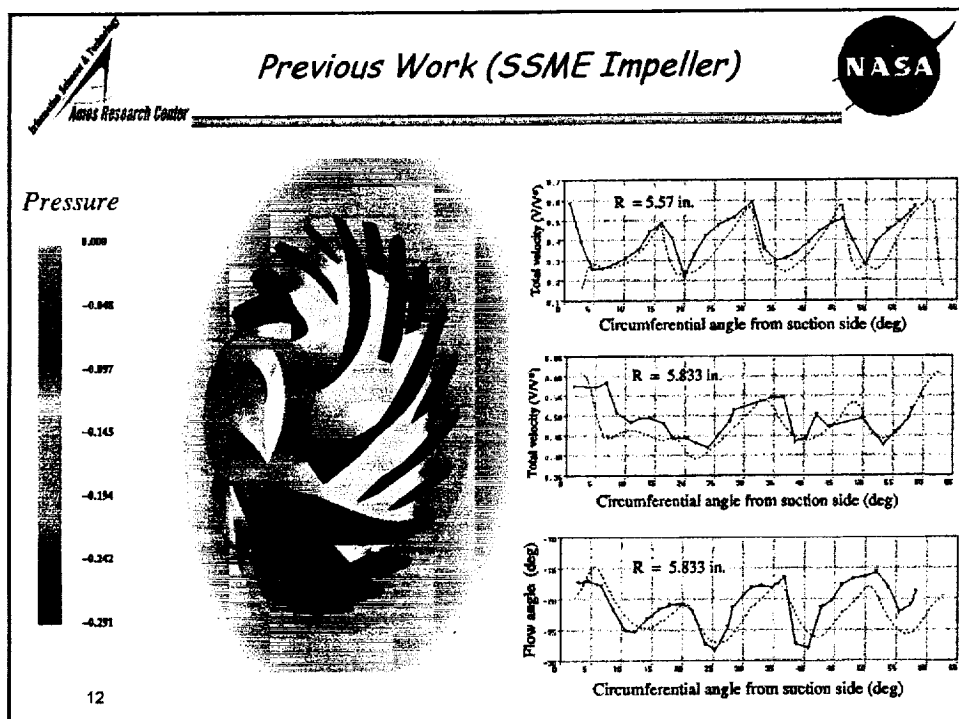Time

9
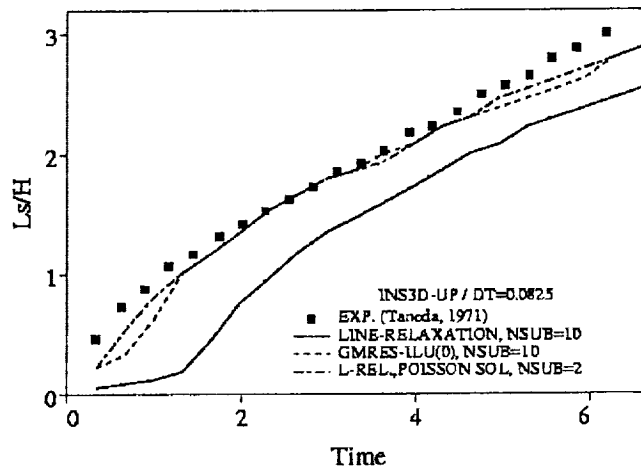
** *Parallel version is based on* INS3D-UP :
- MPI and MLP parallel versions
- Structured, overset grid orientation
- Moving grid capability
- Based on method of artificial compressibility
- Both steady-state and time-accurate formulations
- 3rd and 5th-order flux difference splitting for convective terms
- Central differencing for viscous terms
- One- and two-equations turbulence models
- Several linear solvers : GMRES, GS line-relaxation, LU-SGS,
            GS point relaxation, ILU(0)...,..

- HISTORY
  ** 1982-1987 Original version of INS3D – Kwak, Chang
  ** 1988-1999 Three different versions were devoped :
            INS3D-UP / Rogers, Kiris, Kwak
            INS3D-LU / Yoon, Kwak
            INS3D-FS / Rosenfeld, Kiris, Kwak

10

INS3D Parallelization

- INS3D-MPI
  (coarse grain)

- INS3D-MPI / Open MP
  MPI (coarse grain) + OpenMP (fine grain)
  Implemented using CAPO/CAPT tools
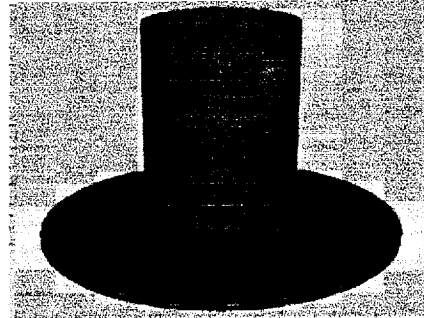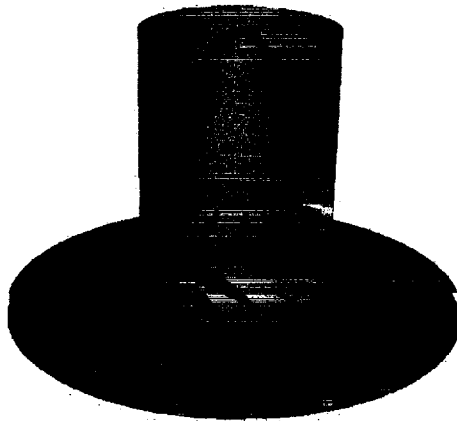
- INS3D-MLP

11

Previous Work (SSME Impeller)

Pressure

12

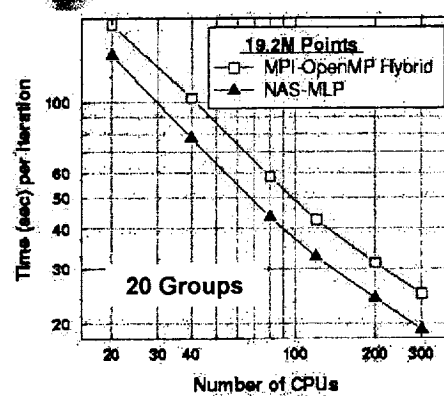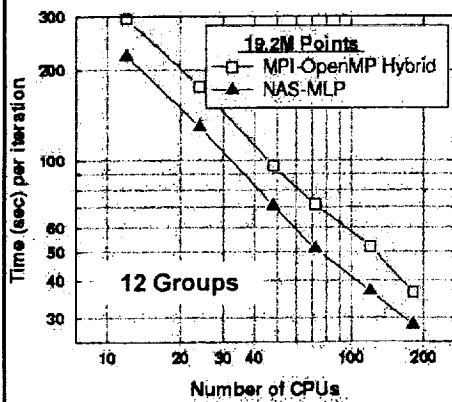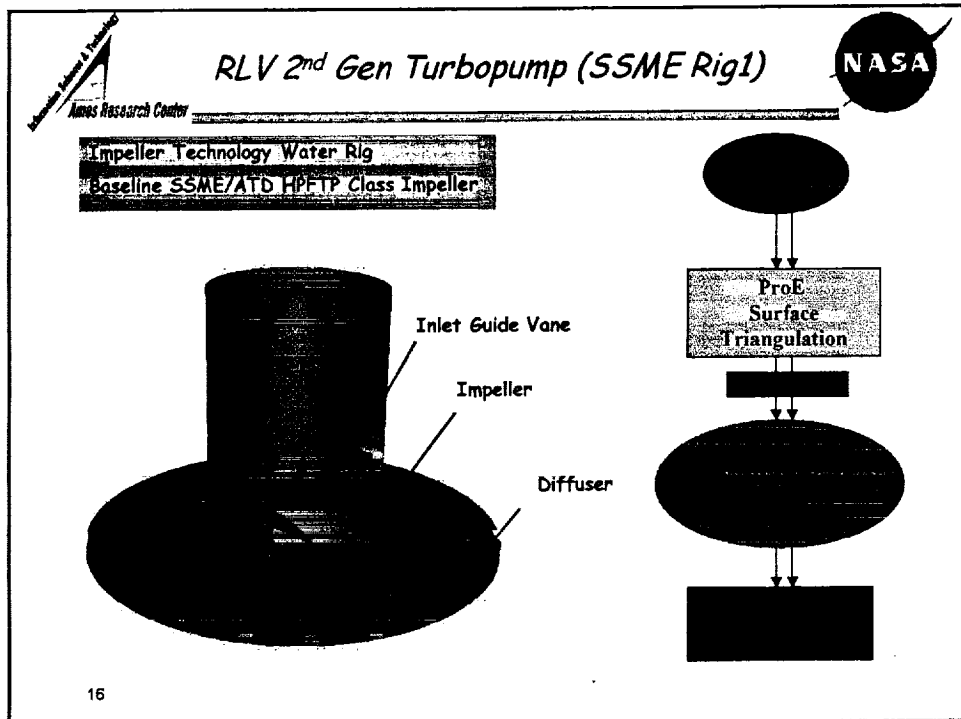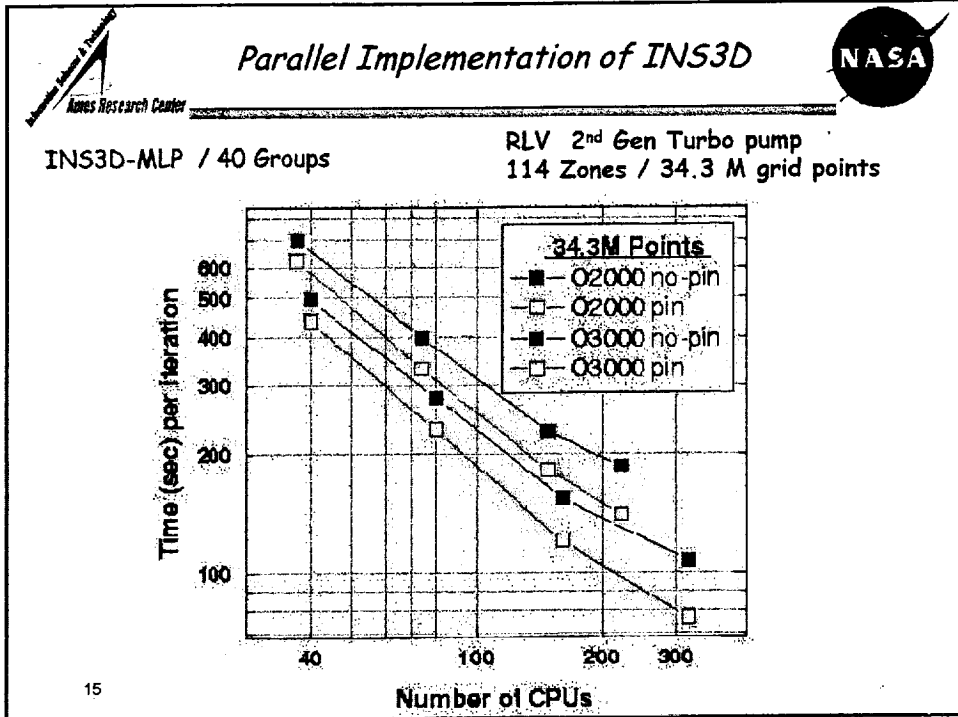Space Shuttle Main Engine Turbopump

13

INS3D Parallelization

INS3D-MLP/OpenMP vs. -MPI/OpenMP

TEST CASE : SSME Impeller
60 zones / 19.2 Million points

12 Groups

20 Groups

14

Parallel Implementation of INS3D

INS3D-MLP / 40 Groups

RLV 2nd Gen Turbo pump
114 Zones / 34.3 M grid points

15

RLV 2nd Gen Turbopump (SSME Rig1)

Impeller Technology Water Rig
Baseline SSME/ATD HPFTP Class Impeller

Inlet Guide Vane

Impeller

Diffuser

ProE
Surface
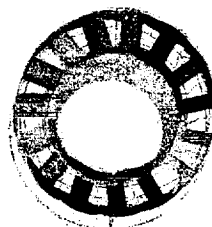Triangulation

16

RLV 2ⁿᵈ Gen Turbopump
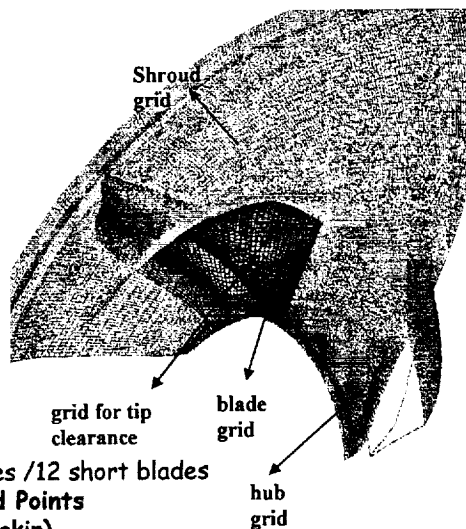
Overset Grid System

Inlet Guide Vanes
15 Blades
23 Zones
6.5 M Points

Diffuser
23 Blades
31 Zones
8.6 M Points

17

RLV 2ⁿᵈ Gen Turbopump

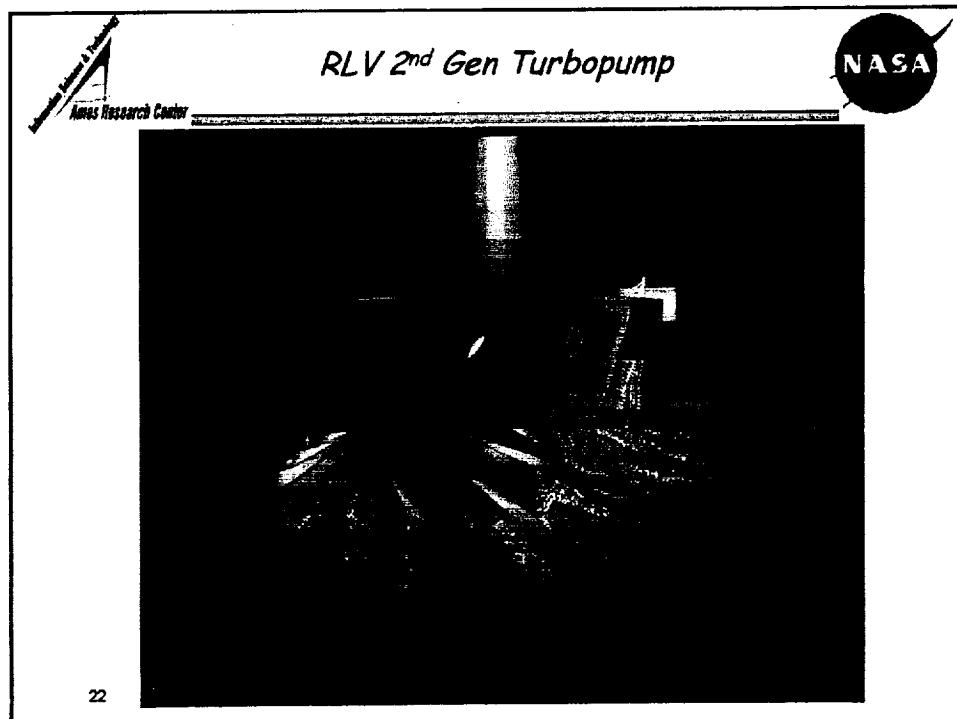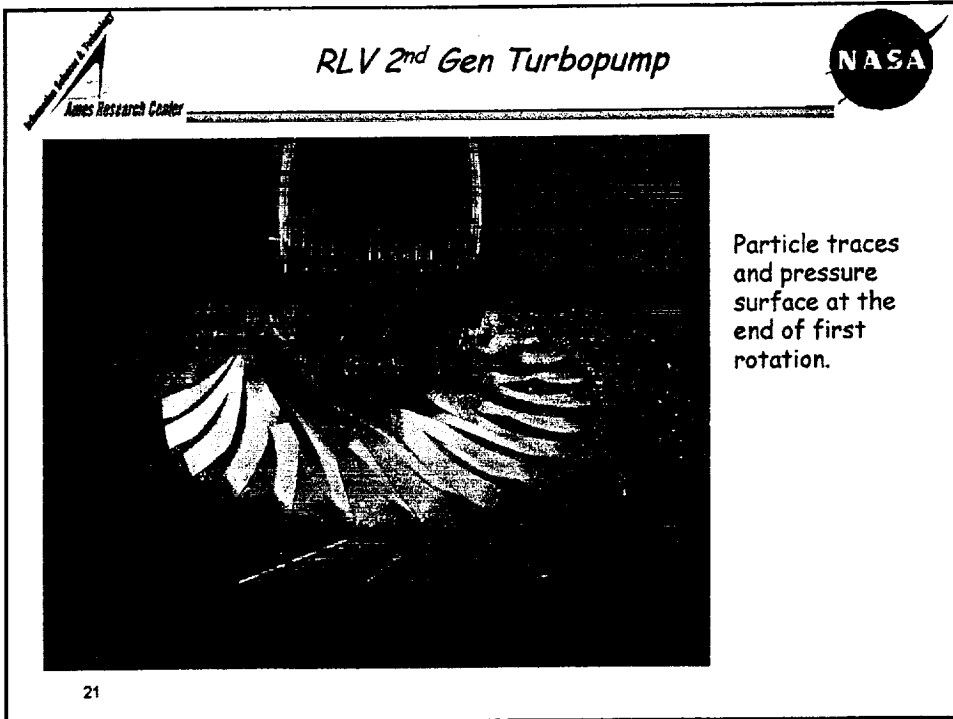Shroud grid

grid for tip clearance
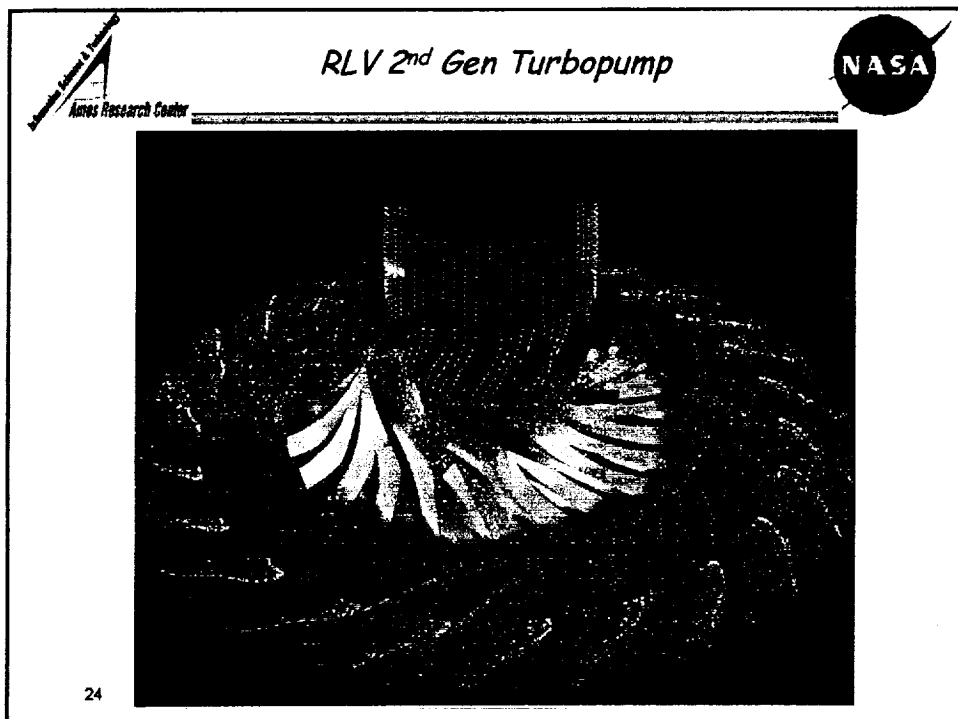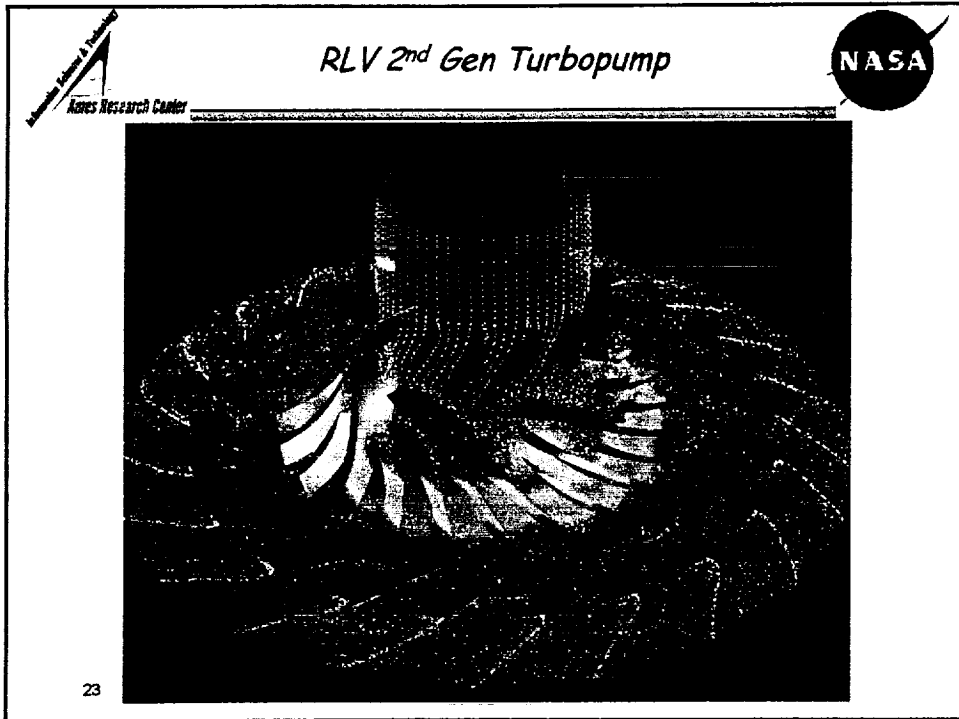
blade grid

hub grid

Unshrouded Impeller Grid :
6 long blades / 6 medium blades /12 short blades
60 Zones / 19.2 Million Grid Points
Overset connectivity : DCF (B. Meakin)
Less than 156 orphan points.

Impeller Overset Grid System

Blade Grid

Background Grid

19

RLV 2nd Gen Turbopump (baseline)

INITIAL START : Impeller rotated 12-degrees

VELOCITY MAGNITUDE

PRESSURE

20

Particle traces and pressure surface at the end of first rotation.
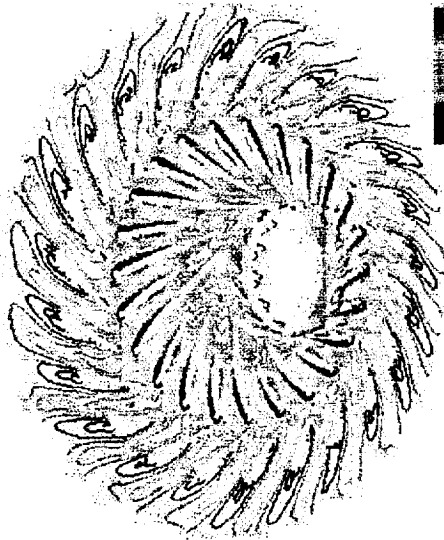
21

22

RLV 2nd Gen Turbopump
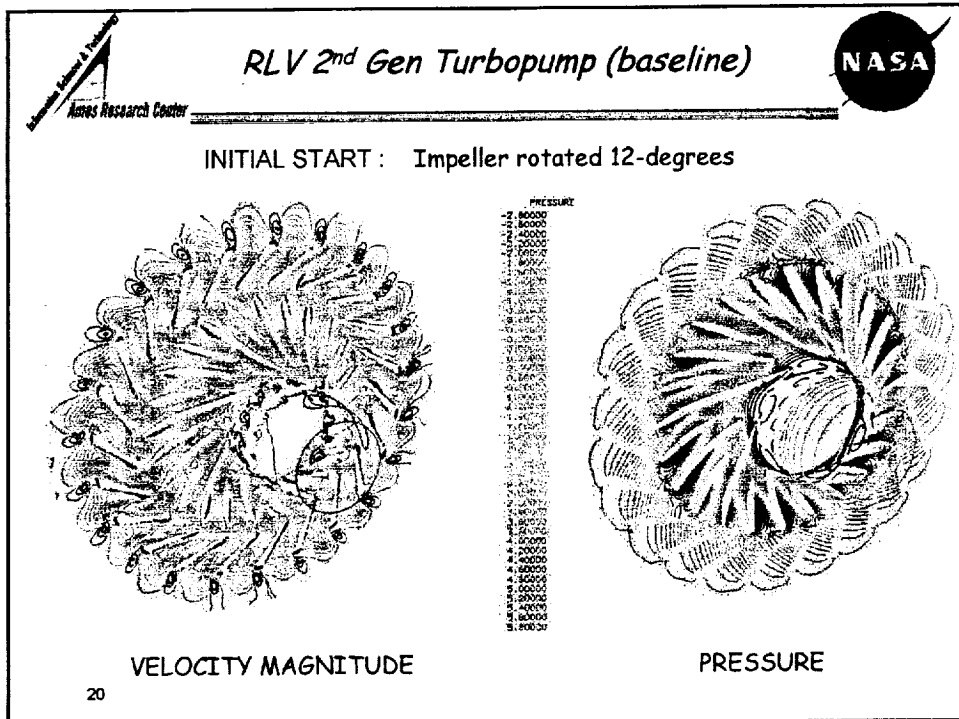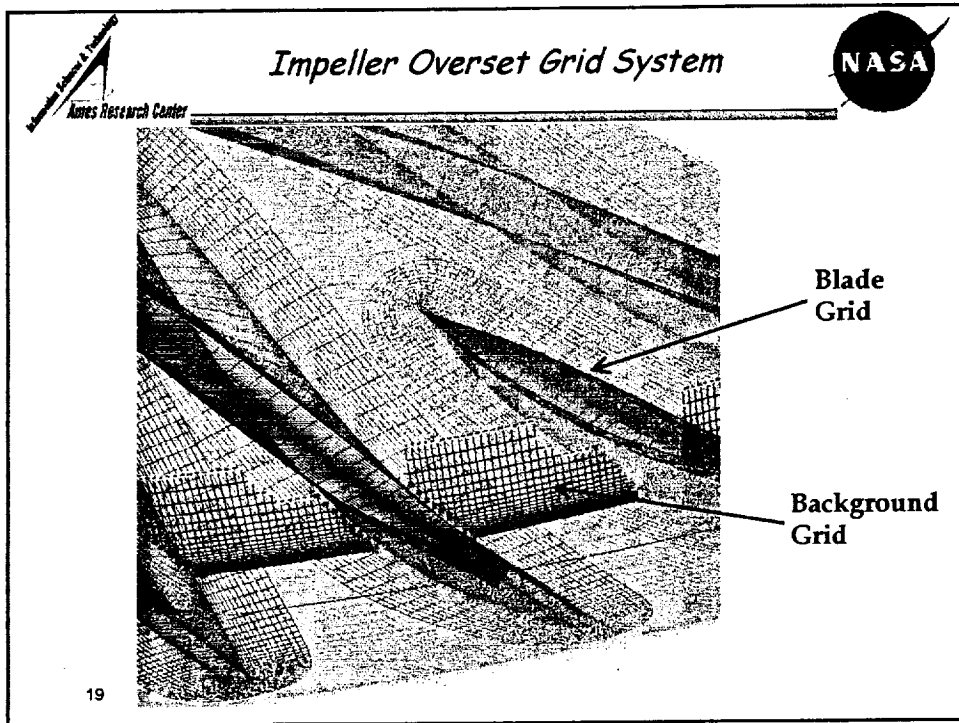
RLV 2nd Gen Turbopump

RLV 2nd Gen Turbopump

VELOCITY MAGNITUDE

1.4

0.0

- 34.3 Million Points
-Two and half impeller rotations are completed.

·One complete rotation requires less then 3.5 days by using 128 CPUs on SGI Origin 3000. When 512 CPUs are utilized one rotation can be completed less then 1.5 days. In 1999, one impeller rotation would take 42 days by using 32 CPUs on SGI Origin 2000 platform.
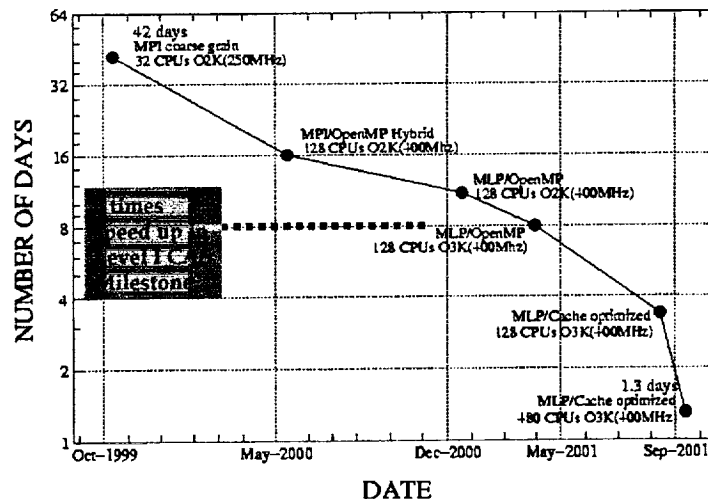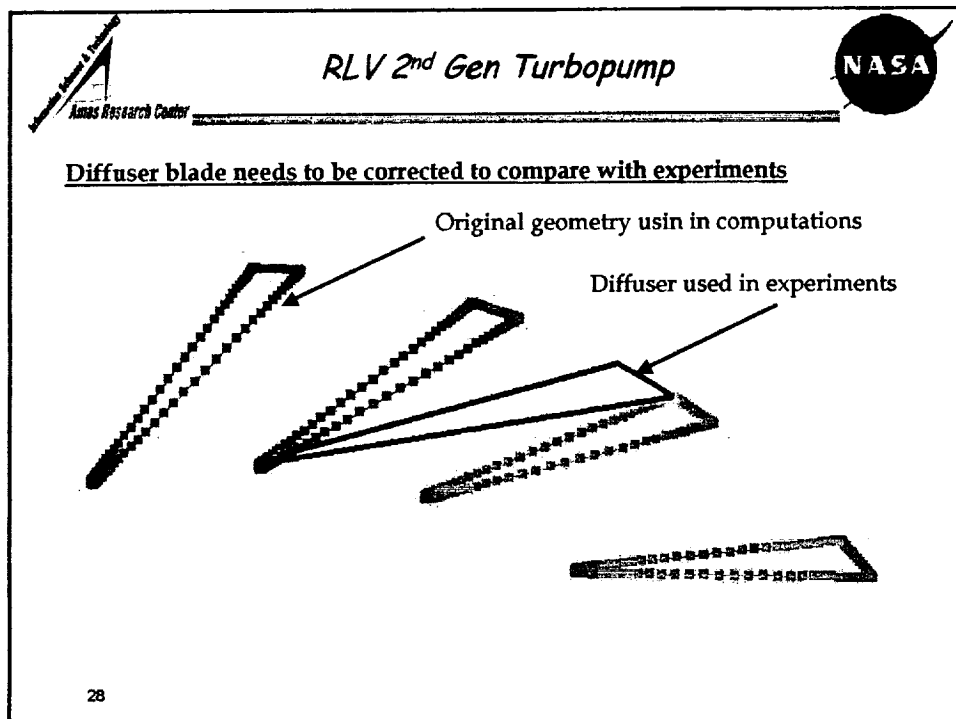

RLV 2nd Gen Turbopump

34.3 Million Grid points RLV Turbopump one impeller rotation

42 days
MPI coarse grain
32 CPUs O2K(250MHz)

MPI/OpenMP Hybrid
128 CPUs O2K(400Mhz)

MLP/OpenMP
128 CPUs O2K(400MHz)

times speed up over IC Milestone

MLP/OpenMP
128 CPUs O3K(400Mhz)

MLP/Cache optimized
128 CPUs O3K(400MHz)

1.3 days
MLP/Cache optimized
480 CPUs O3K(400MHz)

NUMBER OF DAYS

DATE

26

27

Diffuser blade needs to be corrected to compare with experiments

Original geometry usin in computations

Diffuser used in experiments

28

## SCRIPT DEVELOPMENT FOR TURBOPUMP SIMULATIONS

Motivation

Significant user's effort needed
in complex process from geometry
to flow solver

igv

Impeller

Objective

Develop script system to
- generate grids
- create domain connectivity input
- create flow solver input
for different components
automatically

diffuser

GEOMETRY → Turbopump Scripts → DCF → FLOW SOLVER

| grids | domain connectivity input | flow solver input |
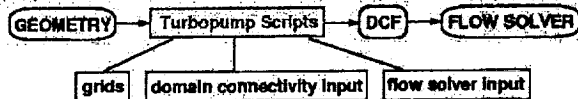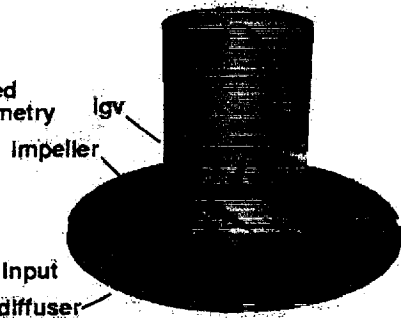
Approach

Develop one script for each component with ring interface
between components => easy plug in for different designs
and combinations of components

29

SCRIPT GENERATION

Disadvantages

> Require expertise to build scripts the first time

Advantages

> Allow rapid re-run of entire process

> Easy to do grid refinement and parameter studies

> Easy to try different gridding strategies

> Documentation of gridding procedure

Tcl scripting language

> Works on UNIX, LINUX and WINDOWS

> Integer and floating point arithmetic capability

> Modular procedure calls

> Easy to add GUI later if needed

30

INPUT AND OUTPUT

Input

> profile curves for hub and shroud in PLOT3D format
(rotated by script to form surface of revolution)

> blade and tip surfaces in PLOT3D format

> Parameters that can be changed
  – number of blades and sections
  – global surface grid spacing Δs (on smooth regions)
  – local surface grid spacing, some independent and some
    expressed as multiples of Δs (leading/trailing edges, etc.)
  – normal wall grid spacing (viscous, wall function)
  – marching distance
  – grid stretching ratio
  – ...

Output

> overset surface and volume grids for hub, shroud, blades
> object X-rays for hole cutters using DCF
> domain connectivity namelist input for OVERFLOW-D

31

INLET GUIDE VANES (N repeated blades, no tip clearance)
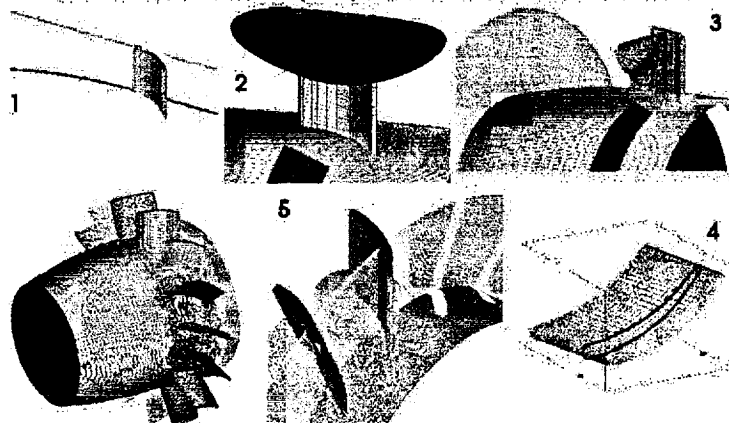
	Manual	Script (fine)	Script (coarse)
No. of pts (million)	7.1	5.8	1.1
User time *	1 day	43 sec.	20 sec.

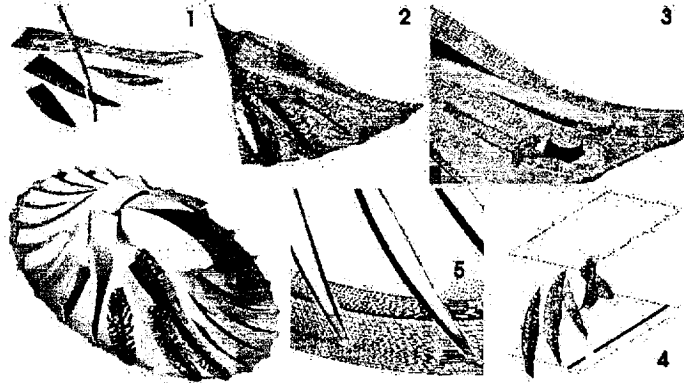(* from geometry def. to DCF input with SGI R12k 300MHz CPU)

32

Scripting Capability

IMPELLER
(M sections, N different blades in each section, tip clearance)

	Manual	Script (fine)	Script (coarse)
No. of pts (million)	19.2	15.2	8.8
User time *	~ 2 weeks	319 sec.	234 sec.

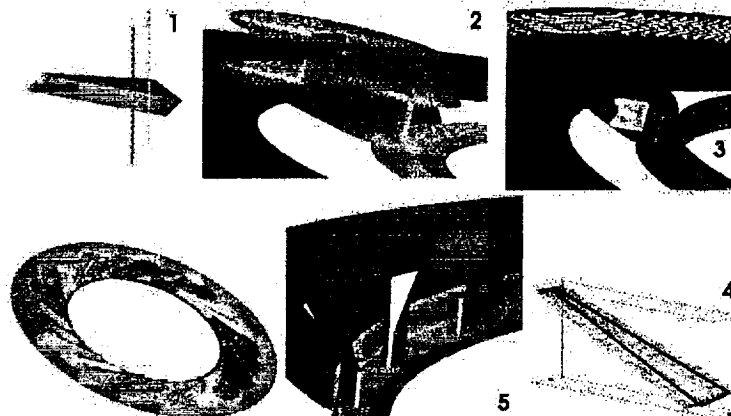(* from geometry def. to DCF input with SGI R12k 300MHz CPU)
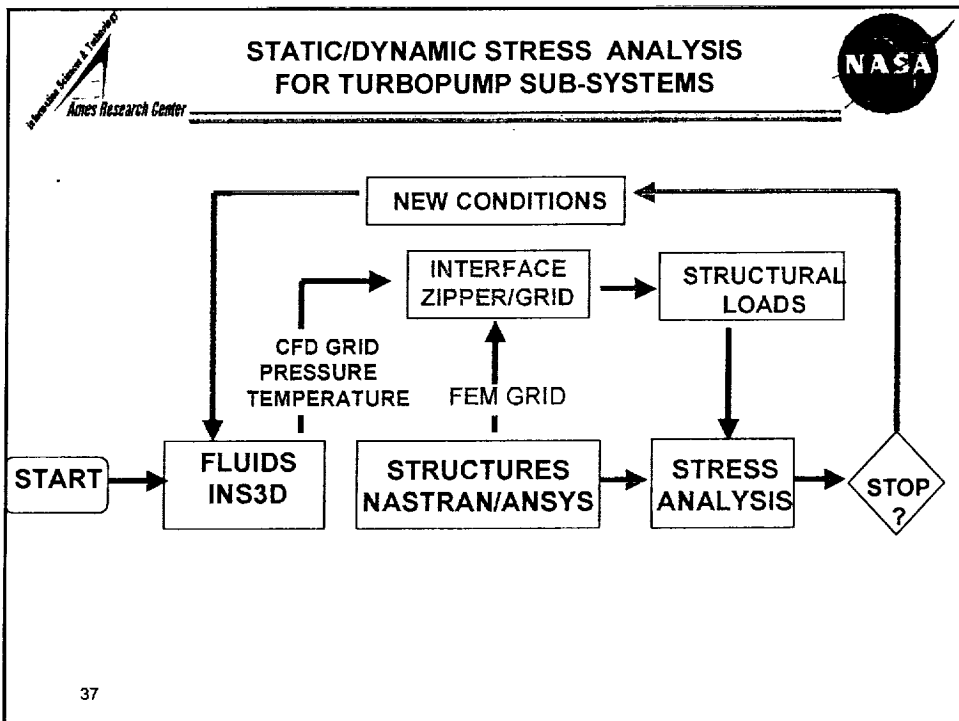
33

Scripting Capability

DIFFUSER (N repeated blades, no tip clearance)

	Manual	Script (fine)	Script (coarse)
No. of pts (million)	8.0	6.4	1.6
User time *	1 day	37 sec.	22 sec.

(* from geometry def. to DCF input with SGI R12k 300MHz CPU)

34

37

Summary

Ames Research Center

NASA

●Unsteady flow simulations for RLV 2nd Gen baseline turbopump for three impeller rotations are completed by using 34.3 Million grid points model.

●MPI/OpenMP hybrid parallelism and MLP shared memory parallelism has been implemented in INS3D, and benchmarked.

●For RLV turbopump simulations more than 30 times speed-up has been obtained.

●Moving boundary capability is obtained by using DCF module.

● Scripting capability from CAD geometry to solution is developed.

●Fluid/Structure coupling is initiated.

38